ARO 23845.1-PH

(2)

OPTICALLY TUNABLE GRATINGS FOR OPTICAL INTERCONNECTS

Final Report

Submitted by

G. I. Stegeman

30 October 1989

Submitted to

U. S. Army Research Office

Grant No: DAAL03-86-K-0143

Optical Sciences Center
University of Arizona
Tucson, Arizona 85721

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) ARO 23845.1-PH
6a. NAME OF PERFORMING ORGANIZATION Optical Sciences Center University of Arizona 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION U. S. Army Research Office
6c. ADDRESS (City, State, and ZIP Code) Tucson, Arizona 85721	7b. ADDRESS (City, State, and ZIP Code) P. O. Box 12211 Research Triangle Park, NC 27709-2211
8a. NAME OF FUNDING / SPONSORING ORGANIZATION U. S. Army Research Office 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER DAAL03-86-K-0143
8c. ADDRESS (City, State, and ZIP Code) P. O. Box 12211 Research Triangle Park, NC 27709-2211	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
Optically Tunable Gratings for Optical Interconnects (Unclassified)

12. PERSONAL AUTHOR(S)
G. I. Stegeman

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 8/1/86 TO 7/31/89	10/30/89	7

16. SUPPLEMENTARY NOTATION
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	optical interconnects; all-optical beam scanner; nonlinear grating coupler; bistable nonlinear grating coupler.

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The properties of a nonlinear grating coupler were investigated for application to an all-optical beam scanner for optical interconnects. En route, this program achieved four distinct goals:

1. Bistability was demonstrated for grating coupling into ZnS waveguides utilizing a diffusive nonlinearity (thermal).
2. It was shown theoretically that a diffusive nonlinearity is required to obtain bistability in a nonlinear grating (or prism) coupler. This cleared up a 5 year controversy in the literature.
3. An all-optical beam scanner was demonstrated in which the scan angle of a signal beam is tuned by varying the input power of the control beam. Both smooth and bistable scanning was implemented.
4. This device was analysed theoretically for both non-local and local (Kerr) nonlinearities. It was shown that Kerr nonlinearities lead to a non-unique response.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL S. Ostrowski	22b. TELEPHONE (Include Area Code) (602) 621-6996 22c. OFFICE SYMBOL

1. INTRODUCTION

An interesting problem in the area of optical interconnects is how to address, through space, multiple chips from a single chip, with optical signals. The problem, essentially, is how one controls the angular direction of an optical beam. Control can be achieved through various physical phenomena, such as acousto-optic or electro-optic deflectors. Using the strengths of our research program, we investigated optically tuneable gratings in integrated optics structures.

We designed and fabricated the beam-steering device shown in Fig. 1. The device consists of a thin-film waveguide with an intensity-dependent refractive index. A grating was ion milled into the glass substrate surface prior to deposition of the film. A high-power (10 mW - 4 W) control beam was coupled into the waveguide by this grating, thereby modifying the refractive index distribution in the coupling region. A second signal beam was coupled out of the waveguide by the same grating coupler. Because the out-coupling angle depends on the refractive index in the grating region, the output angle is determined by the control beam power.

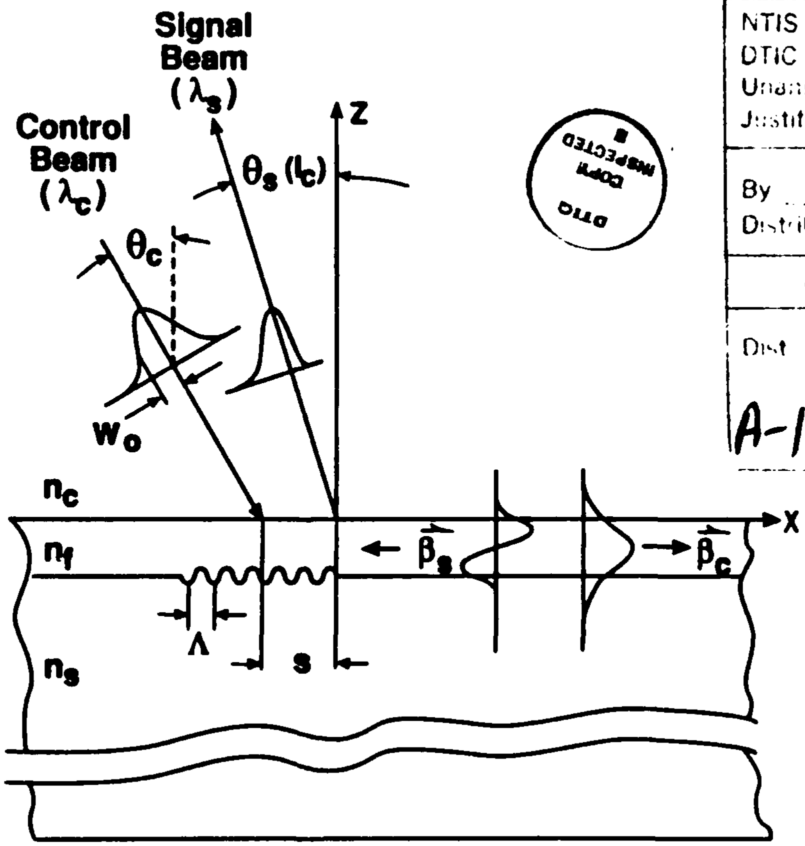


Figure 1. Schematic of the beam-steering device with a grating at the film-substrate interface. The refractive indices n_c, n_f and n_s are, in general, intensity dependent. Here these indices refer specifically to the cladding, film and substrate respectively. Control and signal beams are shown in the TE_0 and TE_1 waveguide modes, respectively.

Our program of research evolved through the following sequence.

1. Fabrication of samples by ion milling gratings into the surface of glass substrates followed by overcoating with ZnS waveguiding films.

2. Measurement of the high-power input coupling properties of the grating coupler.

3. Analysis of the in-coupling process, including, for the first time, diffusive nonlinearities.

4. Demonstration of an all-optical beam scanning device.

5. Analysis of this device for a diffusive (non-local) nonlinearity.

6. Analysis of the device for Kerr (local) nonlinearities.

The theoretical work was accomplished through collaboration with Drs. G. Vitrant and R. Resinisch of LEMO in Grenoble. The experimental work relied on the production of ZnS waveguide films by Prof. U. J. Gibson's group.

2. SAMPLE FABRICATION

We ion milled gratings into the surface of glass substrates, using techniques that have become standard in our laboratory. First, an interference grating was formed in photoresist by the beating of two argon ion laser beams in the photoresist material. Development of the photoresist and ion milling yielded a 0.1-μm-deep grating with a period of 0.3 μm. These parameters were chosen so that only one diffraction grating order could exist at a time, to be coupled into the waveguide.

The waveguide consisted of a 0.62-μm-thick ZnS film ($n_f \cong 2.36$) deposited onto a microscope slide ($n_s = 1.51$). The film was made by ion-assisted deposition for the first 1000 angstroms, and normal thermal evaporation thereafter. ZnS interference filters have been used previously as bistable elements, and the power-dependent change in the refractive index has been identified as thermal (through absorption).

3. HIGH POWER INPUT GRATING COUPLING [1-4]

We investigated the variation in the in-coupled power with incidence angle, using the $\lambda = 515$ nm line of an argon ion laser, which corresponds to the control beam in Fig. 1. The coupling efficiency response with incident angle was Lorentzian, as was theoretically expected. The angular width of this curve established the required coupling angles for observing bistability, which requires an angular detuning of at least one angular linewidth. Power-induced bistability was observed for an incidence angle detuned by 5 linewidths from the low-power case. When the optimum low-power coupling angle was used, the coupling efficiency varied monotonically with increasing incident power.

The key point, found experimentally, is that the "average" refractive index change in the coupling region increases monotonically with power when the incidence angle is chosen to be that which produces optimum coupling efficiency at low powers. If this angle is detuned by several linewidths, a bistable jump in this "average" refractive index occurs.

This coupling process was modelled theoretically by combining coupled mode theory with a diffusive equation describing the non-locality of the nonlinearity. A non-local nonlinearity is a diffusive nonlinearity, such as that encountered in semiconductors, arising from carrier diffusion, or thermal nonlinearities. This analysis was required because, to predict the signal beam out-coupling angle (see Fig. 1), the refractive index in the coupling region must be known.

Some controversy had arisen in the nonlinear integrated optics community, concerning the operation of nonlinear prism or grating couplers. A number of authors have stated that bistability can occur for Kerr nonlinearities, whereas others have stated that only switching can be obtained for local nonlinearities. Researchers working in the area of bistability had apparently been vindicated by numerous reports of bistability in distributed couplers. Our work, however, showed that switching occurs only for local nonlinearities, and that, by introducing non-locality with increasing diffusion lengths, bistability can be produced. Because previous experimental reports of bistability always involved thermal nonlinearities, the requirement for bistability is now clear.

All previous models for nonlinear distributed couplers addressed only local, Kerr-law nonlinearities, a case seldom encountered in practice. Modelling for the non-local case required the simultaneous solution of the diffusion equation along the propagation direction and of the nonlinear coupling equation. After working through many numerical instabilities, we developed an iterative procedure which gave stable, reproducible and physically reasonable results. A confirmation of this procedure's validity was that it reproduced the plane wave result for large input beams. We found that a minimum angular detuning, $\Delta\theta$, is necessary for the bistable response of a distributed input coupler, and that this minimum detuning is inversely dependent on the input beam spot size. Furthermore, we found that the field amplitude required for the bistable threshold was essentially independent of the beam spot size. All of these findings were borne out by our experiments.

Results of our analysis are summarized in Fig. 2, which shows that switching is obtained for purely local nonlinearities (diffusion length D = 0), and that there is a critical D for the occurrence of bistability. Having obtained good agreement with experiment, we can predict the refractive index distribution over the grating region from the strong control beam.

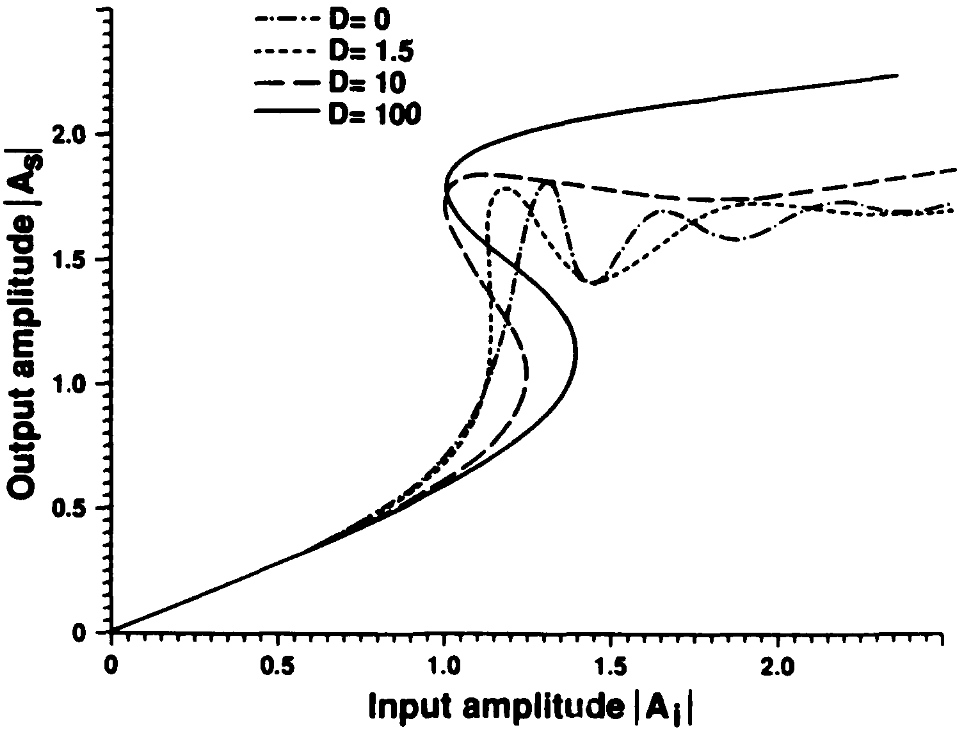


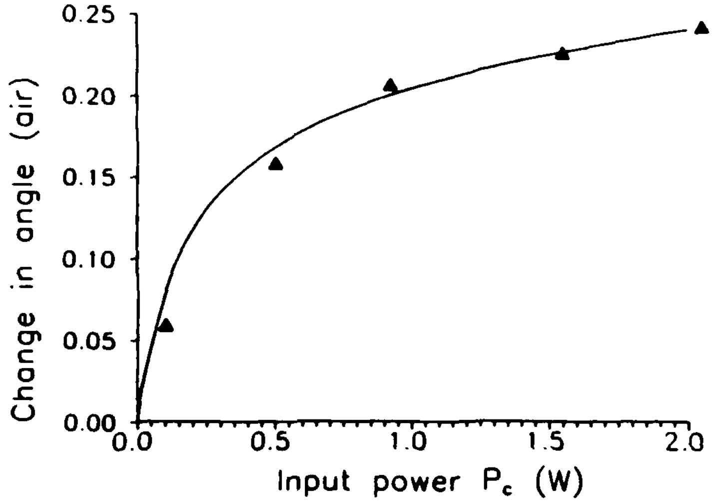
Figure 2. The influence of the diffusion length D on the response of a nonlinear grating coupler. Note the change to a bistable response for D > 1.5.

4. ALL-OPTICAL BEAM SCANNER [1,2,5,6]

In the experiment associated with Fig. 1, an argon ion laser supplied the control beam, and a multiline He-Ne operating in the green-yellow supplied the signal beam. (Not shown in Fig. 1 is the prism used to couple the signal beam into the waveguide.) This device geometry was used to investigate the tuning of the signal beam angle with increasing control beam power, and the response time of the device.

Results are presented in Fig. 3. When the control beam incidence angle is set at its optimum low-power coupling angle, the signal beam angle is scanned monotonically (but not linearly) with control beam power. When bistability occurs during control beam in-coupling, bistability occurs in the scan angle. Scan angles of 0.5^0 were typical. Furthermore, by modulating the control beam power in the "bistable" regime with an acousto-optic modulator, we found the rise time of the scanned beam to be 10 μs.

a)



b)

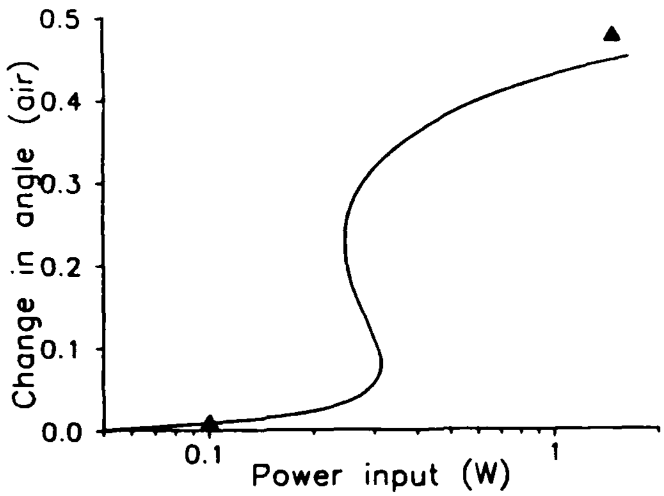


Figure 3. Comparison of the calculated (solid line) and experimental (triangles) results for the change in outcoupling angle of a signal beam at 594 nm in a ZnS waveguide. (a) The waveguide was excited at the low-power optimum conditions, and the signal was in the TE_1 mode. The diffusion length D is 0.6 mm. (b) The device is detuned from the low-power optimum. Note that the change in angle is larger for (b) than for (a) because of angular detuning.

This experiment demonstrated the feasibility of an all-optical beam scanner. Our next task was to analyze the operation of this device to define its limitations.

There are two distinct stages in the analysis. First, an input coupler operating on a non-local nonlinearity must be treated, and the refractive index change produced by the control beam computed. This step was performed as outlined in Section 3. Second, the signal beam must be propagated numerically through this region, and the scanned radiation beam calculated in the far field. A weak scanning beam, out-coupled by the coupler excited by the control beam, was propagated numerically through the coupler. The local out-coupled field was calculated, and the beam then was propagated numerically in space to define the signal beam width and angle in the far field. As shown in Fig. 3, we were able to reproduce, theoretically, the bistable and the smooth (with increasing incident control beam power) beam scanning found experimentally.

Detailed results of the analysis entailed the operation of this device for the two prevalent types of nonlinearity currently available, that is, for (1) local Kerr nonlinearities (as with polymers) and (2) the more frequent non-local diffusive nonlinearities employed in our experiments. The principal differences between scanner response characteristics arise from the response of the input coupler to the two types of nonlinear material. For a Kerr nonlinearity, the in-coupled power oscillates with increasing control beam power, leading to a non-unique output coupling angle with increasing power for the signal beam. This key result is shown in Fig. 4. However, when saturation in the index change is introduced (i.e., when real materials are considered), this oscillation is suppressed, and there is a one-to-one correspondence between the signal output angle and the input control power. For a non-local nonlinearity (i.e., for spatial diffusion of the nonlinear index change in the coupler region), the output angle increases sub-linearly but monotonically with increasing power for a tuned input coupler, and can exhibit bistable jumps at appropriate detunings. In general, the tuning response is smoother if the grating is more efficient as an output coupler than as an input coupler, so that all of the signal light is coupled out over distances that are short in comparison to the input coupling distance.

Conclusions of our theoretical analysis are as follows:

1. The beam scanner response is not useful for a local Kerr-law nonlinearity.

2. With index saturation, the Kerr response becomes monotonic, and useful.

3. Diffusive nonlinearities offer the best characteristics for all-optical beam scanning, both with bistable jumps and with continuous tuning.

4. Improvements in the number of resolvable spots can be obtained with chirped, focusing gratings.

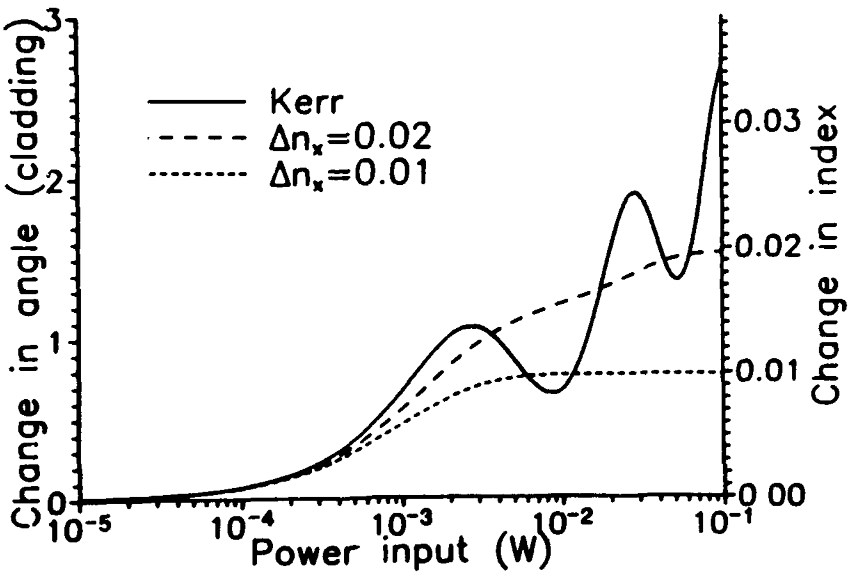


Figure 4. Change in outcoupling angle of the probe beam into the cladding versus incident power for a waveguide exhibiting a Kerr nonlinearity. Pure Kerr and saturable (Δn_x = maximum index change) local cases are calculated with the strong beam in the TE_0 mode. The probe propagates in the TE_1 mode. The vertical axis on the right represents the pump-induced change in effective index.

5. SUMMARY

Under this contract we succeeded in demonstrating an all-optical beam scanner that can be used for optical interconnects. The direction of a signal beam radiated into space can be controlled by varying the power of a control beam. Scanning angles of 0.5° were demonstrated in a prototype device. A theory was developed and proved capable of predicting the detailed operating characteristics for the system. A controversy over input grating couplers was resolved when it was determined that a non-local nonlinearity is required to obtain bistability.

PUBLICATIONS

1. B. C. Svensson, C. T. Seaton, U. J. Gibson and G. I. Stegeman, "Bistability and Beam Steering via Grating Coupling to ZnS Waveguides," presented at CLEO'88, Anaheim, April 1988.

2. B. C. Svensson, C. T. Seaton, U. J. Gibson and G. I. Stegeman, "Bistability and all-optical beam scanning via a grating coupler in nonlinear ZnS waveguide," Appl. Phys. Lett., 53:941-3 (1988).

3. G. Vitrant, R. Reinisch, J. Cl. Paumier, G. Assanto and G. I. Stegeman, "Nonlinear prism coupler with diffusion," Topical Meeting on Nonlinear Guided Wave Phenomena, paper FB3, Houston, February 1989.

4. G. Vitrant, R. Reinisch, J. Cl. Paumier, G. Assanto and G. I. Stegeman, "Nonlinear prism coupler with non-locality," Opt. Lett., 14:898-900 (1989).

5. G. Assanto, G. I. Stegeman and G. Vitrant, "Analysis of all-optical integrated beam-scanning devices," Appl. Phys. Lett., 54:1854-6 (1989).

6. G. Assanto and G. I. Stegeman, "Nonlinear all-optical beam scanner," J. Appl. Phys., in press.

THESES

B. C. Svensson, "Nonlinear Grating Coupler Phenomena in ZnS Waveguides: Beam Scanning, Bistability and Power Limiting," PhD thesis, June 1988.